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Maximal capacity nonorthogonal pulse shape modulation

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Abstract To improve spectral utilization of communication system, a novel nonorthogonal pulse shape modulation (NPSM) based on prolate spheroidal wave function (PSWF) is proposed. The modulation employs nonorthogonal PSWF pulses to transmit information and it shows a higher capacity than traditional orthogonal modulations. The NPSM capacity under the constraint of finite input alphabet, which is determined by parameters of PSWF pulse, is derived. An optimization model for maximal capacity of NPSM is constructed and an exhaustive self-adapting gradient search algorithm for the model is proposed. A practical NPSM scheme with the maximal capacity is obtained by this search algorithm and it is proved to be superior to orthogonal signaling in the capacity. Our theoretical analysis is validated by numerical simulations and practical tests, and the results show that NPSM outperforms orthogonal modulations in the capacity and has a lower Peak-to-Average Power Ratio.

1. Introduction

To achieve high data rate transmission with a finite bandwidth is the eternal pursuit for communication system. The state-of-the-art efficient modulations such as orthogonal frequency division multiplexing (OFDM) and quadrature amplitude modulation (QAM) employ orthogonal sine and cosine functions to transfer information. The orthogonality eliminates intersymbol interference (ISI) and facilitates the demodulation and detection of received signals. However, the orthogonality restriction is a rigid requirement for modulation signals, and it is sensitive to the nonideal channel and hard to maintain. The orthogonality restriction also limits the further improvement of communication system performance. On the other hand, sinusoidal functions have many fine mathematical properties and consequently are widely used in the communication system.

In view of signal energy distribution in the time–frequency domain, the area occupied by the sinusoidal functions in the time–frequency plane is 2 Hz·s, and sinusoidal functions are not excellent in the energy concentration. Moreover, the relative bandwidth of sinusoidal functions is small, which restricts the data rate of communication system.

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The nonorthogonal modulation is a popular research area for efficient modulations. With the Euclidean distance of pulse waveform maintained, Mazo showed that sending sinc pulses up to 25% faster does not decrease the minimum Euclidean distance of modulated symbols by reducing the time spacing between two contiguous symbols.[1,2] Rusek and Anderson studied the constrained capacity of faster than Nyquist (FTN) signaling with i.i.d. modulated symbols on additive white Gaussian noise (AWGN) channel and showed that FTN is often better than the conventional orthogonal signaling.[3] Werner and Andreas proposed a nonorthogonal FDM (NOFDM) system based on nonorthogonal pulses that are adapted to realistically available a priori knowledge of the channel and the results show that the choice of nonorthogonal pulses is optimum for minimizing the ISI and Inter Carrier Interference (ICI) introduced by the non-ideal channel.[4] By optimizing the spacing between adjacent signals to maximize the achievable spectral efficiency, a transmission scheme consisting of the superposition of two independent signals with suitable power allocation and a two-stage receiver was proposed in Ref.[5]. Other nonorthogonal modulation techniques with a high bandwidth efficiency were proposed in Refs.[6–9].

The existing nonorthogonal modulations are designed mainly in terms of time-domain spacing of contiguous pulses and channel characteristics. Although our goal in this paper is similar to the above mentioned works, we explore here a novel design method of nonorthogonal pulses based on prolate spheroidal wave functions (PSWFs). PSWF has the best energy concentration in both the time and frequency domain and its center frequency and bandwidth can be set to any available value, which provides a flexible and effective method to partition signal energy on the time–frequency plane.[10] We analyze the relationship between spectral efficiency and bit error ratio (BER) for PSWF pulses with a high energy concentration, and a capacity optimization model for nonorthogonal pulse shape modulation is established. By solving the model, a transmission scheme of nonorthogonal pulse shape modulation with the maximal capacity is obtained.

The rest of the paper is structured as follows. The nonorthogonal pulse shape modulation based on PSWF pulses is proposed in Section 2. Section 2 also analyses the relationship between spectral efficiency and BER for QAM and nonorthogonal pulse shape modulation (NPSM). The constrained capacity of nonorthogonal PSM is derived and a modulation channel capacity optimization model for NPSM is established in Section 3. By solving the model, an optimal scheme for NPSM based on PSWF (PSWF–NPSM) is acquired. Experimental and test results of the PSWF–NPSM scheme are presented and discussed in Section 4. Finally, some concluding remarks are given in Section 5.

2. Nonorthogonal pulse shape modulation based on PSWFs

2.1. Pulse waveform design based on PSWFs

For the nonorthogonal modulations, system performances are mainly determined by the employed pulses. PSWF was firstly discovered by Slepian and Pollak in Bell Labs.[10] PSWF has a maximum energy concentration between the interval $[-T, T]$ as a bandlimited function, and its bandwidth and time duration can be flexibly set. Wyner proposed a physically consistent model based on PSWF for the time-continuous and bandlimited channel.[11] For the above excellent properties, an Ultra-wideband pulse design based on PSWFs was presented in Ref.[12], and a cognitive radio system based on PSWF was proposed in Ref.[13]. Researches on PSWF were also conducted in satellite communication, code division multiple access (CDMA) and channel estimation.[14–16] The demodulation method for multidimensional constellation signals based on PSWFs is studied in Ref.[17]. Taking the flexibility of pulse design and energy concentration into account, PSWF is the optimal pulse waveform for nonorthogonal pulse shape modulations. Slepian discovered that the PSWF is the eigenvalue function of finite time-domain Fourier transform and the integral equation definition is expressed as

$$\lambda_n \psi_n(c,t) = \int_{-T/2}^{T/2} \frac{\sin(\Omega(t-s))}{\pi(t-s)} \psi_n(c,s)\mathrm{d}s \tag{1}$$

where λ_n is the eigenvalue of the equation and n the order of PSWF. The time-bandwidth product $c = \Omega T$ and Ω is the bandwidth of $\psi_n(c,t)$. Parr et al. gave the definition of PSWF band-limited to $[f_1, f_h]$[12]:

$$\int_{-T/2}^{T/2} \psi_n(\tau) h(t-\tau)\mathrm{d}\tau = \lambda_n(c)\psi_n(t) \tag{2}$$

where $\lambda_n(c)$ is the eigenvalue of the equation and $h(t)$ is the impulse response of ideal filter band-limited to $[f_1, f_h]$:

$$h(t) = 2f_h \mathrm{sinc}(2f_h t) - 2f_l \mathrm{sinc}(2f_l t) \tag{3}$$

The band-limited PSWF $\psi_n(c,t)$ has the parameters of the time duration T, the upper frequency f_h, the lower frequency f_l, the order number n and the time-bandwidth product $c = 2\pi(f_h - f_l)T$. For a given time-bandwidth product c, the number of available orthogonal PSWF pulses with a high energy concentration is $(2c-2)$.[18] Therefore, the Nyquist rate can be rapidly approached by the use of PSWF pulses. For example, non-sinusoidal orthogonal modulation in the time domain (NSOMTD), which employs orthogonal PSWF pulses to transmit information, can rapidly approach Nyquist rate and its spectral efficiency is increased faster than that of OFDM as the number of parallel modulated signals increases.[19] However, further research on the NSOMTD shows that the Schmidt orthogonality procedure will decrease the energy concentration of PSWF pulse and lead to spectral regrowth.

To maintain a high energy concentration of PSWF pulses, the orthogonality restriction for PSWF pulses is given up. Meanwhile, the spectra of PSWF pulses are pairwise overlapped to improve spectral efficiency. The overlapping factor of two contiguous subbands is λ $(0 \leqslant \lambda < 1)$ and the PSWF pulses are designed in each subband. The design of nonorthogonal PSWF pulses proceeds as follows:

(1) Ascertain the subband number M and the overlapping factor λ by the spectral efficiency ρ, and they satisfy:

$$\rho = \frac{M(2c-2)}{c[\lambda + (1-\lambda)M]} \tag{4}$$